NOMAD, A SPECTROMETER SUITE FOR NADIR AND SOLAR OCCULTATION OBSERVATIONS ON THE EXOMARS TRACE GAS ORBITER.

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Introduction:

NOMAD, the "Nadir and Occultation for MArs Discovery" spectrometer suite has been selected by ESA and NASA to be part of the payload of the ExoMars Trace Gas Orbiter mission 2016. This instrument suite will conduct a spectroscopic survey of Mars' atmosphere in the UV, visible and IR regions covering the 0.2-0.65 and 2.2-4.3 µm spectral ranges. NOMAD's observation modes include solar occultation, nadir and limb observations. Its spectral resolution surpasses previous surveys in the infrared by more than one order of magnitude. The nadir mode will provide detailed trace gas mapping.

NOMAD will search for active geology, volcanism and life by looking for their atmospheric markers. NOMAD will confine potential source regions and provide crucial information on the nature of the processes involved. NOMAD will also extend the survey of the major climatologic cycles of Mars such as the water, carbon and ozone cycles, and provide information on their different components, including isotopic fractionation and atmospheric escape processes.

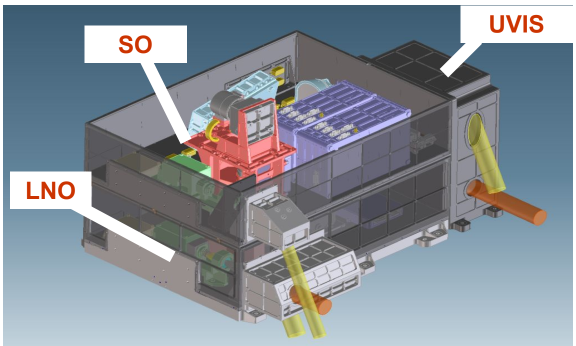

Fig. 1: The three channels of NOMAD (SO, LNO, and UVIS)

The NOMAD instrument:

The Nadir and Occultation for MArs Discovery (NOMAD) instrument is composed of 3 channels: a solar occultation only channel (SO) operating in the infrared wavelength domain, a second infrared channel capable of doing nadir, but also solar occultation and limb observations (LNO), and an ultraviolet/visible channel (UVIS) that can work in all observation modes. The spectral resolution of SO and LNO surpasses previous surveys in the infrared by more than one order of magnitude. NOMAD offers an integrated instrument combination of a flight-proven concept (SO is a copy of SOIR on Venus Express), and innovations based on existing and proven instrumentation (LNO is based on SOIR/VEX and UVIS has heritage from the ExoMars lander), that will provide mapping and vertical profile information at high spatio-temporal resolution. The three channels have each their own ILS and optical bench, but share the same single interface to the S/C.

SO channel. The SO channel operates at wavelengths between 2.2 and 4.3 µm, using an echelle grating with a groove density of 4 lines/mm in a Littrow configuration in combination with an Acousto-Optic Tunable Filter (AOTF) for spectral window selection, see Fig. 2. The width of the selected spectral windows varies from 20 to 35 cm^{-1} depending on the selected diffraction order. The detector is an actively cooled HgCdTe Focal Plane Array. SO achieves an instrument line profile resolution of 0.15 cm^{-1}, corresponding to a resolving power $\lambda/\Delta\lambda$ of approximately 25000.

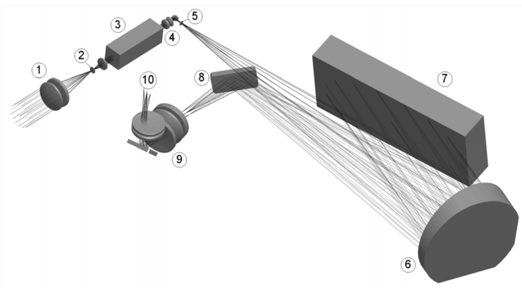

Fig. 2: SO schematics

LNO channel. The optical layout of LNO is identical to that of SO (AOTF - echelle spectrometer-cooled detector, see Fig. 2). LNO will be measuring in the wavelength range between 2.2 and 3.8 µm. To fulfill the SNR requirement, a number of low risk and easy-to-implement measures are taken to increase the signal throughput as well as to reduce the thermal background of the instrument, e.g. increasing the length of the slit from 30' to 100' (but not its width to guarantee the high resolution) and using longer integration times, appropriate pixel binning, and accumulation of spectra. Another solution is to increase the width of the slit, to admit more light, giving a higher SNR, but reducing the spectral resolution. For the LNO channel, a lollypop shape slit is proposed, offering high resolution spectra (same as the SO channel, $\lambda/\Delta\lambda \sim 25000$) as well as spectra at a lower resolution but with a higher SNR value. The latter will be used in nadir for mapping low-abundance species, once the high resolution part has demonstrated their detection.

UVIS channel. The UVIS channel operates in the wavelength domain between 200 and 650 nm. It is a full copy of the instrument designed for the ExoMars lander, with additional telescopic entrance optics for application in orbit.

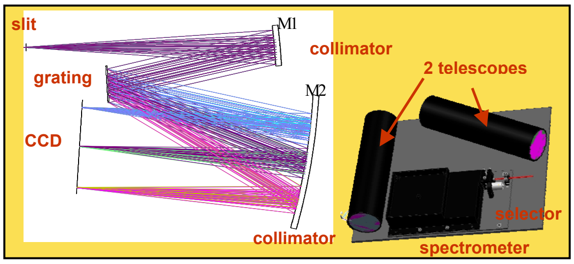

Fig. 3: UVIS schematics

Observation modes:

NOMAD's observation modes complement each other and provide information in different spatial dimensions and at flexible temporal sampling rates:

(1) *Solar occultation* mode provides high-resolution vertical profiles of trace gas absolute abundances together with aerosol extinction, pressure, atmospheric density, and temperature at a vertical sampling equal to or lower than 1 km (in all channels). The duration of a typical SO or LNO measurement cycle is 1 s. Up to 12 different AOTF frequencies can be selected (6 in SO, 6 in LNO), meaning that up to 12 different wavelength intervals can be recorded in 1 s. This provides a total integration and/or accumulation time for each of the selected spectral intervals of 160 ms. If needed, the number of selected wavelength intervals can be reduced, thus increasing the integration time for each interval and hence the SNR. The instantaneous field of view of both channels is limited by the apparent size of the solar disk (21') and by the slit dimension (2', the long side of the slit is parallel to the limb). The resulting field of view corresponds to a 1 km x 10 km slice of atmosphere at the limb ($\Delta z = 1$ km) for typical S/C attitudes. A one-second cycle corresponds to a vertical sampling of 1 km for typical S/C attitudes. Each of the 6 successive measurements performed during this second, however, corresponds to a vertical sampling of 180 m. For UVIS a 1 km x 1 km slice of atmosphere at the limb is probed every 250 ms, leading to a vertical sampling of less than 300 m for typical S/C attitudes.

(2) *nadir* mapping mode provides vertical columns with spatial footprints of 3 km x 12 km and 5 km x 6 km for the high and low resolution LNO measurements, and of 8 km x 5 km for UVIS (for integration times ~ 1 s). As the CO_2 column abundance is retrieved at the same time, systematic error sources (topography, surface shadowing) are eliminated and fractional column densities are determined.

(3) *limb* mode provides limited additional mapping capability and vertical information.

NOMAD sensitivities:

A sensitivity study [1] was carried out to assess the detection limits using a SOIR-type instrument for solar occultation and nadir. This showed that methane concentrations below 1 ppb can be detected from just one spectrum, for a signal to noise ratio based on the SNR values currently observed with SOIR/VEX[2]. The detection limits have been determined assuming a one-second cycle with 6 different spectral windows of 160 ms (SNR=4000). Since several spectra can be recorded per second in occultation, the detection limit can be improved further. It would therefore be possible to go below a 10 ppt detection limit using averaging. The sensitivity study was also performed for nadir observations. The nadir detection limits have been determined for a SNR of 700 for LNO and 1400 for UVIS, leading to sub-ppb detection limit for CH_4.

NOMAD is sensitive to the dust and ice aerosols present in the atmosphere in all three channels, in solar occultation, limb, and nadir viewing modes. In the IR, aerosols are highly scattering; dust does not have any strong spectral features, contrary to ice which has a broad spectral signature around 3 µm. Thanks to diagnostic bands in the IR spectral range NOMAD will also help confirm the controversial detection of carbonates in Martian dust. Aerosol optical depths are derived routinely from solar occultation observations, as has been demonstrated with SOIR/VEX[3]. Measurement of the aerosol opacity across a wide wavelength range (i.e. UVIS, SO and LNO) also allows the optical properties and size distribution of the suspended aerosols to be derived through modeling of the phase function [3]. The presence of ice (both H_2O and CO_2) clouds will be measurable through wavelength-dependent scattering in the observed UVIS spectra.

Spatial and temporal coverage:

NOMAD permits the full exploitation of the orbit. From a 74° inclined orbit, the latitudes covered in solar occultation range from 87°N to 88°S with good revisit time at various solar longitudes (Fig. 4). The nadir coverage between ±74° latitude provides global spatial sampling on average every 3 to 4 sols with varying local times. Due to the nature of the orbit, there will be occasional repeated ground tracks offering better temporal sampling of a given region.

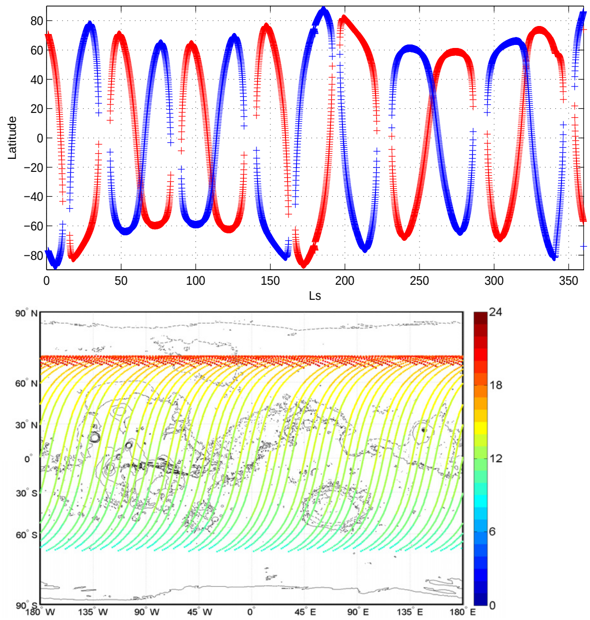

Fig. 4: Latitudes of tangent points in solar occultation versus solar longitude Ls, for sunrise (blue) and sunset (red) (top). Typical example of nadir coverage over 4 Martian sols. Color scale is local time (bottom).

Science objectives:

Detection of Trace Gases and Key Isotopes. NOMAD covers a spectral region from UV to IR that contains signatures of the following molecules, including several isotopologues: CO_2 (incl. $^{13}CO_2$, ^{17}OCO, ^{18}OCO, $C^{18}O_2$), CO (incl ^{13}CO, $C^{18}O$), H_2O (incl. HDO), NO_2, N_2O, O_3, CH_4 (incl. $^{13}CH_4$, CH_3D), C_2H_2, C_2H_4, C_2H_6, H_2CO, HCN, OCS, SO_2, HCl, HO_2, and H_2S. With a resolving power of 25000 (~0.15 cm^{-1}), IR measurements will provide highly resolved spectra of Mars, allowing unambiguous separation of absorption lines and high-sensitivity searches for these trace gases. Nadir observations offer a similar potential for detection. The high sensitivity of NOMAD will offer the possibility to observe as yet undetected species or isotopologues. The detection of the different CH_4 isotopologues ($^{13}CH_4$, CH_3D) will be crucial for the discussion on the origin of this species, and the simultaneous measurement of H_2O and HDO will define the important D/H ratio. UVIS is sensitive to O_3, the most reactive gas in the Martian atmosphere, and SO_2, a gas which can be related to volcanism. Its detection or negative detection is vital to verify present or recent volcanic activity on Mars. NOMAD will also do this for gases related to serpentinization (C_2H_2, C_2H_4, C_2H_6), gases related to clathrates (H_2O and CH_4 as well as dust, ice deposits and temperature profiles), and gases related to volcanic activity such as SO_2 or HCl. In addition NOMAD can detect formaldehyde (H_2CO) which is a photochemical product of methane, as well as N_2O and H_2S which are potential atmospheric biomarkers.

Characterization of Spatial and Temporal Variability. NOMAD will extend the existing atmospheric climatologies for CO_2, CO, H_2O and other trace species, but also for temperatures and total densities. The UVIS channel (200-650 nm) will provide measurements of O_3 in solar occultation (vertical profiles) and nadir (total columns). An improved O_3 climatology will advance our understanding of photochemical processes in the Martian atmosphere, as well as the UV levels on the surface, through the use of radiative transfer modeling of the atmosphere.

Localization of Trace Gas Sources. By measuring aerosols, clouds, surface ices, and vertical temperature profiles, together with H_2O and HDO, NOMAD will directly assess all the components of the water cycle. In addition CO and CO_2 will be measured simultaneously. This will allow us to investigate important production and loss processes for the major cycles: water, carbon, and dust. More generally, source and sink processes for all trace species measured by NOMAD can be investigated in correlation with each other and with dust, ice and temperature profiles, whether they are related to photochemistry, gas-phase chemistry, physical processes (e.g. phase transitions), electrochemical processes in dust storms (triboelectricity), heterogeneous chemistry, or atmosphere-surface/regolith interaction. The NOMAD team has expertise in terrestrial modeling for ozone destruction through heterogeneous chemistry in a 3D model context with detailed online microphysics. This will be extended to the GM3 model to simulate heterogeneous chemistry effects on ozone but also methane and other species. Routines describing interactions with the surface or triboelectricity will be implemented in GM3. For more detailed studies, the microphysical model developed for the Phoenix mission [4] will be applied.

The nadir channels of NOMAD have a spatial footprint between 30 and 300 km^2, depending on the integration time, the upper limit corresponding to nadir detection of 1 ppb of CH_4. With an almost global sampling of the planet within 3 sols, NOMAD will be able to quickly detect any outgassing source region, e.g. plumes of CH_4. Slow seeping will likely lead to a more continuous replenishment pattern originating from the same source region. Simulations of tracer emissions and plumes will be performed using GM3[5]. In an ensemble of forward simulations emerging from various source regions and emission scenarios, the most likely source region and scenario can be confined. As an example, Figure 5 shows a methane plume 3 sols after an impulsive release emission over Nili Fossae of 6.2×10^6 kg of methane from the surface in 30 minutes during local daytime as modeled by GM3.

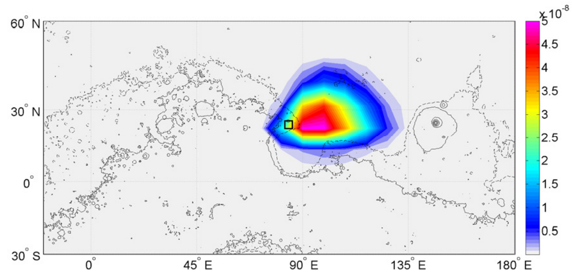

Fig. 5: CH_4 plume (column fraction) 3 sols after an impulsive release at Nili Fossae (square = source) at L_s=150° as calculated by GEM-Mars.

The search for plume sources will be refined by techniques such as:
back trajectory calculations - to track the wind fields back from the detected plume to the regions of origin or to specific atmospheric patterns, e.g. local dust storms or peculiar clouds; with the zoomed mode of GM3, simulations will be possible to a scale of ~ 1 km x 1 km,
inverse modeling - to estimate the emission flux, and
dynamical data assimilation - to provide improved wind fields by constraining the model calculations using dust and temperature measurements. The NOMAD team will also exploit its expertise in chemical data assimilation[6] to achieve a global picture of the Mars atmospheric composition constrained by NOMAD measurements

The NOMAD SO and LNO solar and limb observations will be extremely useful to test the hypothesis that the sources of trace gases, including CH_4, could be related to airborne particles, e.g. clathrates, as suggested recently. PFS limb measurements indicate the existence of CH_4 layers which may be related to such airborne production processes.

NOMAD can not only localize sources, it can also help to explain them. Altered minerals, a key to the understanding of Mars' past and the role of the water on its surface, exhibit diagnostic bands in the NOMAD IR spectral range. The recent detection of phyllosilicates, sulfates and carbonates by OMEGA/MEX and CRISM/MRO indicates that Mars likely sustained liquid water over long periods of time. These sites are considered to be among the best targets for future *in situ* laboratories to find potential biorelics at microscopic scale. With the LNO SNR and spectral resolution, the nadir observations permit measurements of such constituents in phyllosilicate-rich and sulfate-rich regions and to measure the water content within the surface soil and rocks. Detection of magnesium carbonate in the Nili Fossae region reported by CRISM/MRO will be confirmed. New classes of minerals (such as nitrates or carbonate-rich deposits) will be identified, if present. Finally, these measurements will aid in the selection of the landing site for 2018 rovers by providing valuable additional surface composition information.

H_2O and CO_2 ice and frosts also exhibit specific IR signatures in the 3.0-4.0 μm range, which reveal information on the texture and size of the ice grains. NOMAD will discriminate the microphysical state and coexistence modes of water and CO_2 ices in the polar caps and their role, if any, as a possible source of methane. Moreover distinct reservoirs will be distinguished through their different D/H ratio.

Conclusions:

NOMAD is a versatile instrument recording easily any spectral interval chosen for the detection of specific targets, within its range; with optimized integration time (signal level) for each interval; achieving a high vertical resolution in solar occultation mode; offering simultaneous detection of selected species; insensitive to S/C micro-vibrations; with modest data rate; and with flexible observation planning driven by discoveries.

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References
1. Drummond, R., et al., Planet. Space Sci., **In Press**, (2010)
2. Mahieux, A., et al., Optics Express, **17**, 2005-2014 (2009)
3. Wilquet, V., et al., J. Geophys . Res . **114**, doi:10.1029/2008JE003186 (2009)
4. Daerden, F., et al., Geophys. Res. Lett., **37**, (2010)
5. Neary, L., et al., in *EGU 2010*, (2010)
6. Errera, Q., et al., Atmos. Chem. Phys., **8**, (2008)